A 3U CUBESAT MISSION TO IMAGE POTENTIALLY COLLIDING OBJECTS

Giulio Campiti [(1)], Giuseppe Brunetti [(1)], Caterina Ciminelli [(1)]

[(1)]Optoelectronics Laboratory, Politecnico di Bari, 70125, Bari, Italy, (+39) 0805964392, giulio.campiti@poliba.it

[(1)]Optoelectronics Laboratory, Politecnico di Bari, 70125, Bari, Italy, (+39) 0805963044, giuseppe.brunetti@poliba.it

[(1)]Optoelectronics Laboratory, Politecnico di Bari, 70125, Bari, Italy, (+39) 0805963404, caterina.ciminelli@poliba.it

ABSTRACT

This paper introduces a candidate mission concept for the implementation of the first satellite mission of the Polytechnic University of Bari (Italy), whose launch is scheduled for the first half of 2027. The mission, currently in its conceptual design phase, plans to deploy a 3U Cubesat in Low-Earth Orbit, equipped with an electro-optical payload to make observations of objects passing close to the satellite. The objective is a partial demonstration of an autonomous concept of collision avoidance system being developed at the university, based on exploiting independent satellite observations to improve the accuracy of collision predictions. The preliminary mission analysis, payload selection and system design are presented in this work. The selected orbit is a dusk-dawn Sun-synchronous orbit at ∼530 km of altitude, which maximises encounter opportunities under favourable visibility conditions, while also ensuring compliance with debris mitigation requirements. The approach angles of the expected targets have been studied to evaluate the type of pointing required for the observations. Particularly challenging is the design of the communication subsystem due to an expected large data volume generated onboard, which has been assessed following an analysis of the encounter rates performed through System Tool Kit's Conjunction Analysis Tool.

1 INTRODUCTION

The escalating number of conjunction warnings and collision avoidance manoeuvres (CAMs) in Low-Earth Orbit (LEO), driven by the ever-growing number of orbiting objects, is interfering with nominal satellite operations and causing revenue losses to spacecraft owners/operators. However, most CAMs are currently performed as a result of the large uncertainties available on the predicted position of hazardous objects at the Time of Closest Approach (TCA) [1]. A promising approach to improve the accuracy of collision events predictions is to exploit optical sensors onboard satellites to autonomously track objects predicted for potential collisions during the orbits before TCA. The acquired data would be used directly onboard to refine the positional knowledge of the observed object, starting from initial estimates provided from the ground, leading to an accurate assessment of the collision risk and an informed manoeuvre decision. Compared to the traditional ground-based decision-making process, this concept streamlines the interval between orbit determination and the TCA, thereby reducing the uncertainties on the propagated position of the hazardous object. In fact, due to the insufficient accuracy of the surveillance data currently used for collision risk assessments, almost all avoidance manoeuvres executed in LEO are actually unnecessary, wasting satellite time and resources.

Such a concept of avoidance system is at the base of "PoliBaSat", the first satellite mission of the Polytechnic University of Bari (PoliBa), aiming to launch a 3U CubeSat into Low-Earth Orbit (LEO). Specifically, PoliBaSat will give partial proof of feasibility for this concept by demonstrating the extent to which an at-risk satellite can acquire optical tracking data on hazardous objects during the lead-time to TCA. Findings from the on-orbit experiments will be crucial for further advancing the development of the system.
This paper provides an overview of the mission, currently in its conceptual design phase, by presenting the preliminary mission analysis, payload selection and system design.

2 MISSION DESCRIPTION

The Cubesat will be equipped with an electro-optical sensor, either a star tracker or a small camera, which will be used to attempt observations of objects predicted for oncoming close approaches. The Concept of Operations (ConOps) foresees that the satellite receives daily updates of Two-Line Elements (TLEs) for all objects predicted to approach within 10 km of its position for the following 24 hours. Such orbital information will be propagated onboard to identify favourable visibility opportunities and to schedule observation plans. All images will be downlinked and processed on the ground to assess to what extent they could be used onboard to refine the collision risk estimate before TCA. Images are not processed directly onboard because the algorithms needed for this task will only be developed afterwards by tailoring them on the specific image features obtained, such as astrometric and photometric properties. The observed targets are expected to present a low Signal to Noise Ratio (SNR), which can be maximised by training the algorithms to recognise recurrent image patterns arising from the orbital dynamics involved. An extensive analysis of those images will also allow to improve the observation strategy and to determine an optimal SNR threshold to be used for discriminating target signals from noise.
The following are some of the mission's high-level requirements:

- the mission shall be launched within the first half of 2027
- the mission shall comply with ESA's Space Debris Mitigation Requirements, ECSS-U-AS-10C Rev.1 [2].

A CubeSat platform has been selected for this mission both because of the limited budget available and due to the simplicity of its design, making it the standard practice for university-class missions. Based on similar projects, a budget of 200k€ can realistically afford Cubesats up to 3U. In the case of PoliBaSat, a 3U form factor has been selected because of multiple factors, among which:

- Payload accommodation: to capture images of orbiting objects, even a miniaturised star tracker would suffice as a payload, easily fitting inside a 2U Cubesat. However, to maximise the scientific return of the mission, it was decided to opt for a payload that would not have overly limiting features (such as optical apertures below 2 cm), improving detection rates in orbit. Further details on the payload selection process are provided in Section 3.2.
- Need for high data rates: the requirement to downlink images, coupled with the short and infrequent ground-station accesses typically available to Cubesats missions in LEO, result in required data rates in the order of Mbps, as elaborated in Section 2.3. Achieving such data rates demands more complex communication systems than the UHF- or VHF-based typically employed in 1U/2U Cubesats, such as those using S- or X-band frequencies, which are found on Cubesats starting from 3U.

3 CUBESAT DESCRIPTION

3.1 Functional description

The following points outline the primary functions that the satellite shall execute and reflect a preliminary draft of the operational and functional requirements for the mission:

- Image acquisition: the spacecraft shall capture images of at least 1000 objects predicted for an oncoming (< 1 day) close approach (< 10 km). For each target, at least two observation attempts shall be made, provided that favourable visibility conditions are available. The two attempts shall be spaced at least 10 minutes apart and take place no later than 30 minutes prior to the TCA. For each attempt, at least 6 images of the target object shall be captured in rapid succession (exact timing TBD). More details on the observation strategy are given in [3].
- Data transmission: the spacecraft shall downlink all images generated by the payload (compression-quality trade-off TBD) and the telemetry data to the ground; the spacecraft shall also be able to receive command data and orbital information (current specification: TLEs) on the target objects.
- Data handling: the spacecraft shall be able to 1) propagate both its orbital state and that of the target objects, 2) schedule observation plans, including the definition of a timeline and the sensor pointing directions, 3) generate attitude control commands to according to the planned observation schedule. The onboard software shall also feature reconfiguration capabilities, to allow for updates in the observation strategy.
- Navigation: the spacecraft shall be able to autonomously determine its position in real-time when performing observation scheduling activities.

Additional requirements, not explicitly mentioned, concern usual subsystem functions such as generating and storing electrical energy or ensuring an appropriate thermal environment.

3.2 Payload envelope characteristics

The recently released “AURICAM” camera [4] by Sodern has been selected following a preliminary market survey, mainly aimed at finding the best trade-off between size constraints and detection performances. AURICAM is based on the same architecture as Sodern’s “Auriga” star tracker, from which it inherits several features. Its envelope characteristics are reported in Table 1.

Table 1. AURICAM envelope characteristics [4]

Dimensions	140 x 71 x 65 mm (including baffle)
Mass	< 0.42 kg
Power budget	< 2 W

The only possible arrangement of the camera within the Cubesat is to have its lens covering one of the two “small” surfaces (10x10 cm), a standard practice for 3U CubeSats equipped with cameras. Importantly, AURICAM features programmable integration time (60 μs – 30 s), which is required by the prescribed observation strategy [3] to maximise the SNR of the detected targets. AURICAM is predicted for an IOD (In-Orbit Demonstration) with ESA in 2025. However, it should be noticed that the selected payload is not definitive. Therefore, the above specifications can be seen as upper bounds for the payload’s SWaP.

3.3 Operational orbit and preliminary subsystems definition

A preliminary operational orbit has been selected by accounting for multiple factors, including subsystem design and constraints. The analysis started by considering orbital regions that ensure frequent observation opportunities for the satellites, which requires the mission to target populated orbits. Fig. 1 on the left shows the spatial density of space debris for different altitudes and declinations in LEO, obtained using ESA's MASTER 8.0.3 debris environment model. In the simulation, objects larger than 5 cm have been considered, given that the space-based observations will target objects already identified from ground-based sensors, whose current detection capabilities are limited to minimum object sizes of approximately 5-10 cm.

Polar regions at altitudes of ~ 800 km appear to be the most congested with debris. However, the debris mitigation requirements force the satellite to de-orbit within 25 years after the end of its lifetime, imposing an upper limit to the feasible altitudes. Fig. 1 on the right shows an estimation of the natural decay times for a 3U Cubesat at different altitudes. The analysis has been made by using the model of altitude reduction due to drag reported in [5] and by considering a drag coefficient C_D of 2.2, average solar activity, and a cross-sectional area of 0.01 m^2 exposed to the air flux (worst-case for a 3U CubeSat).

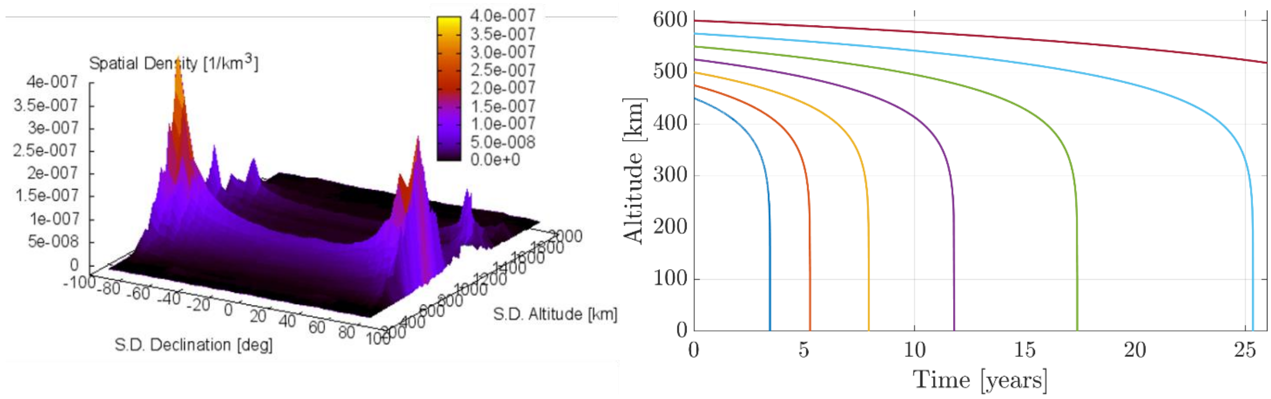

Figure 1. Left: Spatial density of debris objects >5 cm in LEO. Right: orbital decay times for a 3U Cubesat.

Given the multiple sources of uncertainty affecting decay times estimations, altitudes approximately lower than 550 km should be targeted to comply with the 25-year policy. Employing a propulsion engine for actively de-orbiting the CubeSat has been considered, but ultimately deemed not convenient due to SWaP limitations. Although the debris requirements prevent targeting the most debris-populated regions, it should be noted that altitudes around 450 – 550 km are the most crowded with active payloads, as reported in ESA's 2023 Annual Space Environment Report [6]. SpaceX's "Starlink" constellation contributes particularly to the statistics, counting more than 5,000 satellites distributed in different orbital planes at around 540 km as of November 2023. Since the avoidance system is intended for generic hazardous objects, both payloads and debris objects are potentially good targets for the observations. Moreover, given the rapidly accelerating launch rates in LEO, risky conjunctions between active satellites are becoming always more common.

The orbit preliminarily chosen for the mission is a circular one at an altitude of 535 km, which ensures regular observation opportunities with the Starlink satellites while avoiding risky close approaches. The decision to opt for a null eccentricity is based on a recent study carried out at PoliBa [1], which shows that repeated encounters between potentially colliding objects occur as far as their orbits are nearly circular with similar radii. Additionally, piggyback launch opportunities usually target circular orbits.

The remaining orbital parameters are selected to obtain a dusk-dawn Sun-Synchronous Orbit (SSO). This choice follows several considerations regarding the relative positioning of the spacecraft with respect to the sunlight, which affects the illumination conditions during the encounters as well as the onboard solar power generation. Dusk-dawn orbits minimise eclipse time, during which orbiting objects would be generally invisible to onboard optical sensors. Then, the SSO choice ensures that the dusk-dawn condition – namely the orbit's alignment with the terminator line – is met throughout time. Furthermore, the dusk-dawn SSO allows an easier fulfilment of the type of pointing required for the observations, which has been assessed by studying the approach angles of hazardous objects during the orbits before TCA. It was found that their elevation angle with respect to the spacecraft's local horizon plane takes on values of about -10° when the relative distances are still >1500 km, then it gradually reaches 0° as the objects advance further. Instead, the azimuth angles exhibit a broader range of values, but their distribution is notably skewed towards 0° (or 360°), meaning that most objects approach with a head-on geometry. It is concluded that controlling the CubeSat's attitude to always align the sensor in the direction of motion and with a slightly negative elevation (e.g., -5°) would minimise the slew manoeuvres required before the observation attempts. Keeping such pointing direction while in a dusk-dawn SSO conveniently allows the Sun to fall always outside the sensor's Field of View (FoV), fulfilling any requirements on solar exclusion angles.

Considering the typically large size of imagery data, it is essential for the design of the communication subsystem to estimate both the data volume generated in orbit and the frequency of downlink opportunities. Firstly, an estimation of the expected encounter rates in orbit has been carried out using the System Tool Kit's Conjunction Analysis Tool (STK CAT). The CubeSat's nominal orbit has been propagated for a one-week interval starting from December 9, 2023, and its trajectory has been screened against propagated TLEs of all publicly catalogued objects in LEO, to identify conjunctions with relative distances < 10 km. The positional uncertainties in the tangential, cross-track and normal directions have been set to (0.2, 0.1, 0.05) km for the Cubesat and to (1, 0.5, 0.25) km for the other objects, respectively. 218 conjunctions have been found in one week, namely ~15.5 per day. For each conjunction, the CubeSat is assumed to attempt two observations, one and two orbits before the event, respectively. The availability of such opportunities has been assessed in [1]. Knowing the image size and assuming that 10 images are acquired at each attempt (the requirement is ≥ 6), it is possible to estimate the generated data volume over time.

AURICAM's detector grid is made of 20482 pixels and its bit depth comes in two versions, either 10 or 12. The former is chosen to minimise the amount of data generated, resulting in an image size of 20482 x 10 = 41943040 bits (~5 MB). By combining the information on the observation rates with that on the image size, a graph of the data volume generated over time can be drawn, as shown in Fig. 2 on the right. In the first approximation, the plotted data volume curve can be seen as a linear function with a slope of 641 Mbits/hour. Image compression will be applied, which can typically reach high efficiencies for starfield images since most of their pixels are black and represent background noise information. It is assumed that a compression ratio of 1:5 can be applied without encountering severe quality losses.

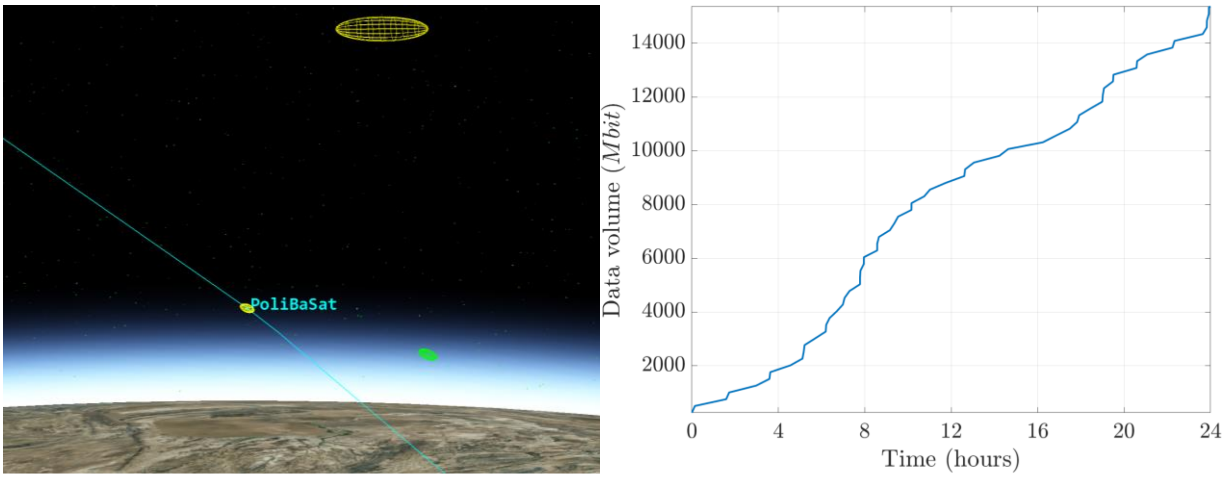

Figure 2. Left: STK snapshot displaying PoliBaSat and a few conjuncting objects with their associated positional uncertainty ellipsoids. Right: Onboard generated data volume (before compression).

Data-rates estimation requires combining the information on the amount of downlink data with that on the ground station (GS) access frequency. PoliBaSat will rely on a single GS – as done by most university-class missions – which is preliminarily selected from Estrack's network. The access frequency between the designed operational orbit and each Estrack's GS has been evaluated on STK by imposing a minimum elevation angle of 10°. As expected for nearly polar orbits, GSs located in polar areas provide the best access frequency. Particularly, the Svalbard and Troll GSs provide 11 and 10 access with mean durations of 6.9 and 6.6 minutes, respectively. Assuming 10 daily accesses of 6 minutes, of which 4.5 are allocated to payload data downlink, a data rate of 1.14 Mbit/s is calculated. Such requirement can be achieved using An S-band communication system; in particular, Endurosat's S-band patch antenna and transmitter, with transmission speeds reaching up to 25 Mbit/s, are selected in this preliminary phase for the payload data downlink. Additionally, a UHF transceiver and associated antenna are foreseen for the downlink of housekeeping telemetry and uplink of data and commands.

For the Electrical Power System (EPS), solar panels stand as the natural choice for the primary energy source given the excellent solar exposure enabled by the dusk-dawn orbit. Since the onboard camera will be pointed towards the direction of motion for most of the time, a body-mounted solar panel on one of the lateral surfaces (30 x 10 cm) was initially considered in the design. Based on an initial power budget estimate, the peak power requirement is calculated to be <15 W, including a 20% safety margin. Taking similar 3U CubeSat missions as a reference, the solar panel is assumed to comprise 8 pairs of 39x69 mm gallium arsenide (GaAs) cells with an efficiency of 30%. Considering the peak power requirements, a minimum of three such solar panels is calculated to be necessary, achieving peak values of 23 W. Consequently, in addition to the body-mounted panel, two additional deployable panels are required on the same face to meet these power needs. The EPS also requires to include a secondary battery for two reasons: 1) despite the dusk-dawn orbit, brief eclipse periods do occur as the terminator line shifts slightly over the year, and 2) during target observations, pointing directions may not always allow for optimal solar panel alignment with the Sun, requiring an alternative power source to maintain uninterrupted operations. The 30 Whr Clyde Space OPTIMUS battery has been selected in this conceptual phase.

Regarding the ADCS, the pointing requirements are primarily driven by the operational modes for target observations and ground communications, though they are not overly demanding. The greater challenge lies in executing the necessary attitude manoeuvres because rapid wide-angle turns may occasionally be required to transition between different observation targets. A detailed analysis of the required slew angles and rates has yet to be carried out. Based on experiences from similar missions, a combination of four reaction wheels and three magnetorquers is deemed suitable for providing three-axis attitude control. For attitude determination, two Earth-Horizon Sensors and multiple (number TBD) sun sensors are initially chosen, taking into account the substantial solar exposure of the orbit and the spacecraft's orientation with respect to the Earth.

The proposed OnBoard Computer (OBC) is the GomSpace NanoMind Z7000, with a SpaceWire connection to the camera.

Lastly, the Cubesat structure is selected from the available COTS (Commercial-off-the-shelf) ones offered on the market. As a baseline, the 3U structure of ISIS Space made in Aluminum 6061 has been selected because of its weight of only 0.24 kg, which is lower with respect to the competitors' average.

4 CONCLUSIONS

This paper introduced "PoliBaSat", the first satellite mission of the Polytechnic University of Bari. The selected technological experiment involves the partial demonstration of an autonomous collision avoidance system for satellites, reflecting a key research area of the university within the space domain, namely Space Traffic Management. An overview of the activities performed so far has been provided, including the preliminary mission design and payload selection. Key initial design decisions include the selection of a 3U Cubesat form, equipped with a camera roughly 1.5 U in size, and intended for deployment in a dusk-dawn Sun-synchronous orbit at ~530 km of altitude. Stringent requirements come from the ADCS, due to significant slew manoeuvres, and from the communication subsystem, where anticipated data rates indicate the need for an S-band system. While the design choices presented provide an initial blueprint of the mission, major design changes might become necessary as the project advances into its next phase of development.

5 REFERENCES

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